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MEMBRANE EVAPORATOR/SUBLIMATOR INVESTIGATION

(TASK ORDER NO. 181)

REPORT NO. 74-10256

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SECTION I

PROGRAM SUMMARY

PURPOSE

The purpose of the membrane evaporator/sublimator (Task Order 181) program was to develop data on a new evaporator/sublimator concept using a hollow fiber membrane unit with a high permeability to liquid water. The aim of the program was to obtain a more reliable, lightweight and simpler Extra Vehicular Life Support System (EVLSS) cooling concept than is currently being used.

SCOPE

The membrane evaporator/sublimator program consisted of evaluating possible materials to be tested as an evaporator/sublimator, running tests on various units in a vacuum chamber to test out the feasibility of the concept and then to analyze the results of the program in order to obtain a design integrated with a recirculating thermal control water loop. By direction of NASA, testing was halted after two materials had been tested.

INTRODUCTION

Semi-permeable membranes are thin, solid films through which different molecular species diffuse at different rates. Thus, they are potentially applicable to many different mass transfer separation processes, as well as phase separation processes in zero-g. Previously, these membranes were fabricated in flat sheets; the flat sheets presented a major obstacle to the full utilization of semi-permeable membranes. A large amount of structure was required to hold flat membranes and a seal was required around both sides of each flat sheet. In addition, each sheet had to be supported in order to maintain even a moderate pressure differential (or driving force) across the flat, thin surface.

Recently, semi-permeable membranes have been developed in the form of very small (30 to 250 microns) hollow fibers. These hollow fibers are essentially tubes and, because of their small diameters, can withstand relatively high pressures. This configuration solves the flat sheet problem of supporting high differential pressures across thin films. A large number of these tubes can be epoxied together at each end of the flow length. Finally, the hollow fibers and epoxied ends are inserted into a metal or polymeric tube, which contains manifolds at each end and an exit port along the tube. The final configuration, shown in Figure 1-1, is similar to a single pass tube and shell heat exchanger. Thus, with the emergence of a technique to make hollow fiber type semi-permeable membranes, a lightweight unit can be designed to withstand high pressures and yield higher mass transfer areas than are obtainable with flat sheet membranes. This hollow fiber type of unit is the one used in the current program.

In this program, a hollow fiber membrane unit was used in a novel way, as a simultaneous mass transfer and heat transfer device. Referring to Figure 1-1, recirculating warm water from the water thermal control loop enters the tube side of the membrane. As the liquid water flows down the length of the tube, some of the water permeates through the thin tube fiber walls and changes phase to gaseous water within the shell of the unit. The heat for this phase change comes from the water flowing down the tube and, thus, this water is cooled. The water is then collected in the outlet plenum and flows out of the unit. The amount of cooling obtained is a function of several variables, including water inlet temperature, pressure on the shell side, type of material the unit is made of and the thickness of the tube wall.

SUMMARY OF RESULTS

Two available membrane units were tested in a vacuum chamber. In one unit the hollow fiber material was cellulose acetate and in the other unit the material was cellulose. Both units achieved a cooling rate in excess of 12000 Btu per hour (the test units weighed about one pound net). The cellulose acetate unit operated successfully only as an evaporator; it froze when operated as a sublimator. The cellulose unit operates successfully in both the evaporation/sublimation regimes. The test was highly successful and proved out the concept of cooling by permeation through semi-permeable membranes. The specific cooling capacity of the unit (BTU/lb of unit) was several times greater than that obtained with present configurations.

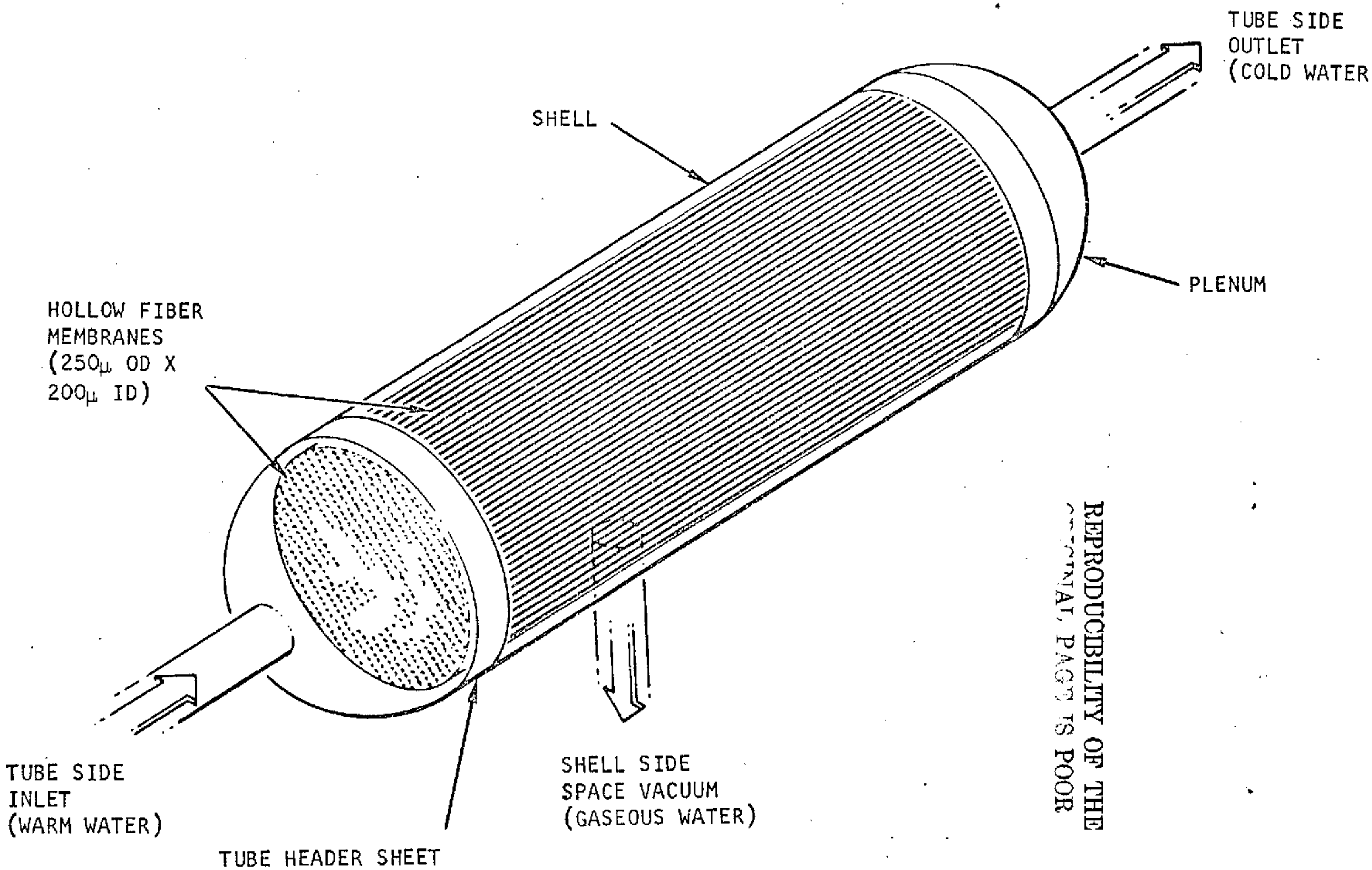

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Figure 1-1. Membrane Unit Configuration

Based on the results obtained during the test program, preliminary designs were made to meet the problem statement shown in Table 1-1. The designs are based on the laboratory test unit and are simply a scaled down version of the laboratory test unit using the same material and tube size.

TABLE 1-1

EVAPORATOR/SUBLIMATOR PROBLEM STATEMENT

Water Flow, Rate, lb/hr	240
Pressure, psig	50
Allowable Pressure Drop, Max psi	1
Heat Rejection	
Maximum	
Btu/Hr	3088
Inlet Temperature, Min, ^{o}F	54
Minimum	
Btu/Hr	135
Inlet Temperature, Max, ^{o}F	80

The sublimator design using a cellulose membrane is shown in Figure 1-2. Preliminary data indicate that this simple straightforward approach can handle the wide range of heat load specified. Estimated weight of the unit is only 0.6 lb.

A concept was also developed for the membranes operating as an evaporator. Here, the basis for the thermal control scheme was the highly reliable steam/thermal control valve used in the Gemini ELSS. This preliminary design is shown in Figure 1-3, weight of the unit is 2.4 lb. Before selection of the best concept can be made, further development testing will be required.

RECOMMENDATIONS

The following program plan is recommended for the next phase of work on the membrane evaporator/sublimator. It is based on the results obtained to date and proposes the development of a unit for a specific problem statement.

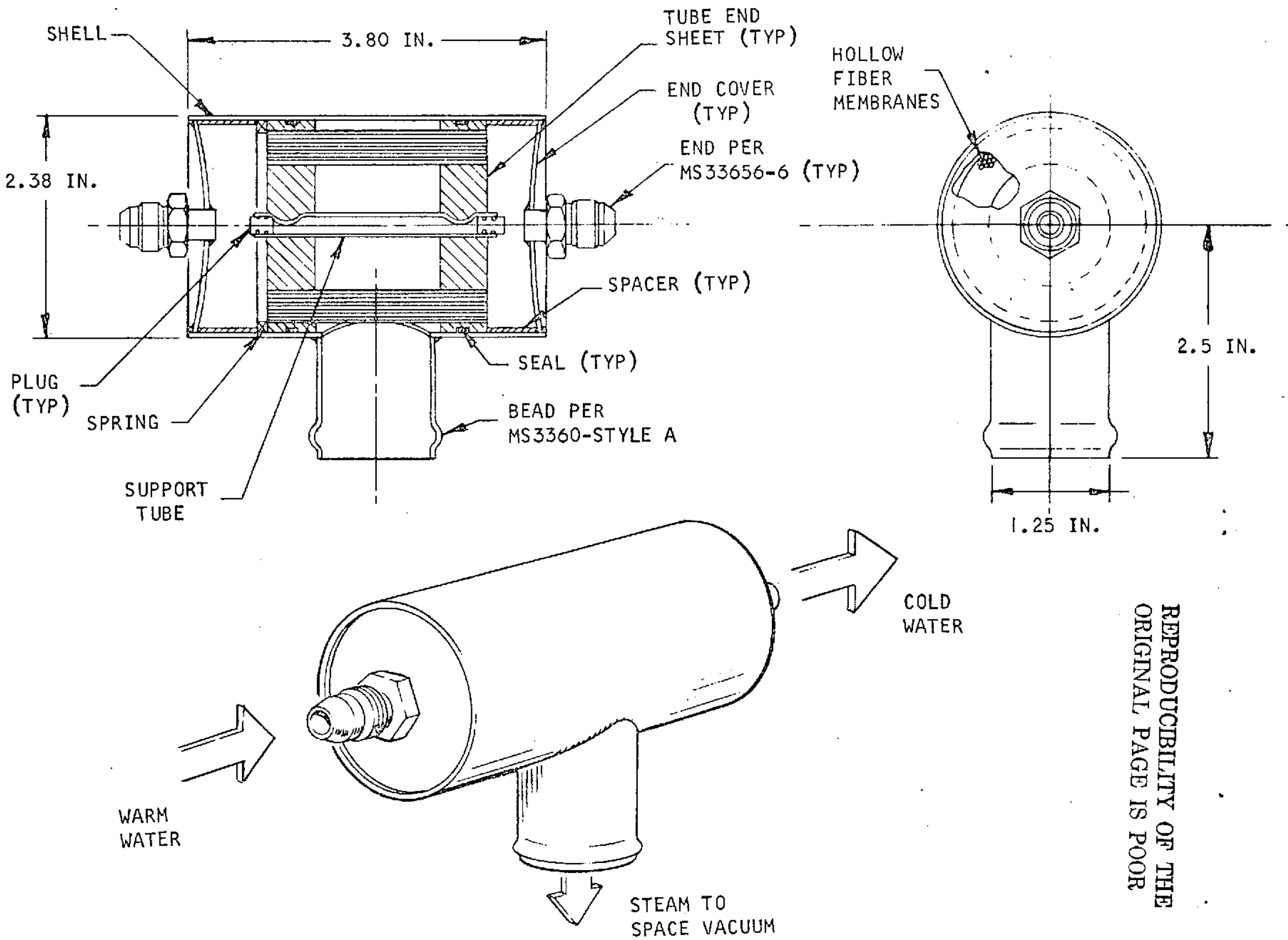

Figure 1-2. Membrane Sublimator

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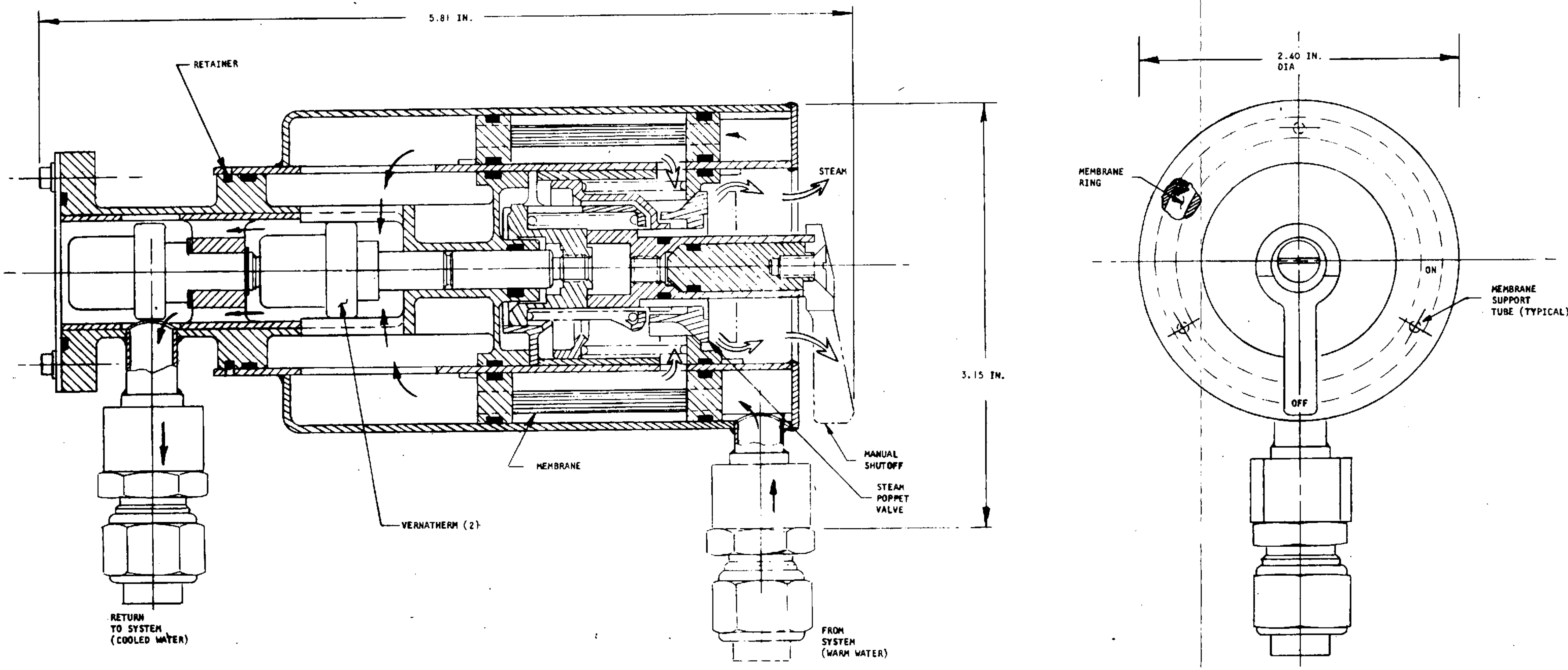

Figure 1-3. Membrane Evaporator

1. Laboratory Tests

Additional tests will be conducted using cellulose in the sublimation regime with widely varying heat rejection requirements. Tests will also be conducted with a new anisotropic, non-cellulosic material. For the new material, permeability and performance tests will be conducted and compared with the data obtained with the cellulose unit. One of the units will be selected for further evaluation testing. This testing will include pre and post performance burst tests, an evaluation of a bactericide on cooling performance and fiber strength tests.

2. Analysis and Design

Analyses will be performed to evaluate the data obtained with the laboratory unit. This will then be used to design a unit to a specific problem statement. The design analysis will include the evaluation of the control system required for integration into an EVLSS.

3. Fabrication and Verification Tests

A unit will be fabricated and tested to verify its performance. Testing will include the effect of inlet water pressure, temperature, rate and chamber pressure on heat rejection. In addition, a vibration test will be conducted to verify the integrity of the unit.

4. Documentation

Results of the analytical, design and test effort will be documented in a final report. In addition, recommendations will be made for the follow-on effort leading to a qualified unit.

SECTION 2

MEMBRANE TEST PROGRAM

INTRODUCTION

Several possible available hollow fiber materials were evaluated for use as an evaporator/sublimator. The most promising materials found were cellulose and cellulose acetate, as shown in Table 2-1. The wide range of permeability values, for a given material, shown in Table 2-1 is due to using material made by various different manufacturers and using various different testing techniques. These materials have extremely high permeability constants for water vapor and, thus, would result in relatively small units. Late in the test program a non-cellulosic, anisotropic type unit was found which was reported to have high permeability rates; however, the program ended before this material could be evaluated.

Available hollow fiber membrane units made of cellulose and of cellulose acetate were bought and tested. The characteristics of the units are:

Tube size, microns	250 O.D. x 200 I.D.
Mean surface area, ft^2	12.2
Number of fibers	9640
Active tube length, inches	6.5

Because the cellulose acetate material has a higher permeability constant for water and has slightly better structural characteristics than cellulose, it was initially tested. The units, as bought, are used for liquid to liquid type diffusional separation processes and have relatively small outlet ports on the shell side. For use under vacuum conditions, it was necessary to open the shell side area to allow the high volumetric flow rates of steam to pass out of the unit without a restrictive pressure drop. The unit was initially modified by cutting slots in the shell to increase the flow area, later the whole shell was removed and the unit was placed in a special fixture that was designed to hold the tube end sheets and the water plenum chamber. In addition, special water plenum chambers made of stainless steel were used so that a load could be applied to the O-ring to seal off and prevent leaks from the water plenum chamber to ambient.

TABLE 2-1

FIBER WATER PERMEABILITY AND STRENGTH CHARACTERISTICS.

Material	Permeability* at 25°C	Tensile Strength at Yield, psi	Elongation at Yield percent
Cellulose	1350 - 13,500(1) 33,000(2)	——	——
Cellulose Acetate	11,200(1) 410 - 54,000(2) 1500 - 10,600(3)	——	——
Polymethyl Pentene	850 - 960(4)	4×10^3(4)	2(4)
Polyethylene Terephthalate	130 - 230(3) 282(5)	1.3×10^4(6)	3 - 4(6)

*Units (cm^3(STP) - cm/cm^2 - sec - cm Hg) $\times 10^{10}$

(1) P.M. Hauser and A.D. McLaren, Industrial and Engineering Chemistry, 40, 112 (1948).

(2) R.M. Barrer, Diffusion in and Through Solids, Cambridge University Press, London, 1951, p. 394.

(3) A. Lebovits, Modern Plastics, 43, 139 (1966).

(4) International Chemical Industries, Technical Bulletin, No. 252.

(5) M. Salame, Problem Solving with Plastics Symposium, NACE, 1971, p. 82-86.

(6) L. Amborsk and D.W. Flier, Industrial and Engineering Chemistry, 45, 2290 (1953).

TEST SYSTEM DESCRIPTION

The purpose of the test program was to obtain basic data on a hollow fiber membrane unit when used as an evaporator/sublimator. A recirculating test loop was built using deionized water as the test medium. The membrane unit was placed in a large vacuum chamber, which was connected to a high capacity vacuum pumping system. Figure 2-1 is a picture of the test setup and Figure 2-2 is a schematic of the setup.

Tests were run by starting up the recirculating water system and obtaining steady state flow conditions. Then the chamber would be evacuated and the heater would be turned on; by manual adjustment of the chamber vacuum valve and of the variac heater control, the desired chamber pressure and water inlet temperature to the unit would be achieved. The test components shown in Figure 2-2 are described in Table 2-2.

TEST RESULTS

The first series of tests were conducted with the cellulose acetate unit. Initially, tests were conducted to determine the permeability of water vapor through the unit when the unit was pressurized with water in air. Results are given in Figure 2-3 for two different serial number units after the shell was removed. Then the pressure drop through the unit was determined using deionized water while the unit was in air. Results of that test are shown in Figure 2-4.

Finally, a series of performance tests were conducted with the cellulose acetate unit located in the vacuum chamber. Initially a series of long term, steady-state tests were conducted in order to evaluate the utilization of water in the evaporative cooling mode. This was done by running in a steady state cooling condition for several hours and monitoring the rate that water was lost from the system. Three data points are shown in Table 2-3.

Then a series of performance tests were conducted to obtain data at various inlet pressures and temperatures, flow rates, and chamber pressures. The results of these tests are also shown in Table 2-3. Also shown in Table 2-3 are data obtained with free water dripping from the unit. The amount of free water was estimated by assuming 20 drops per milliliter.

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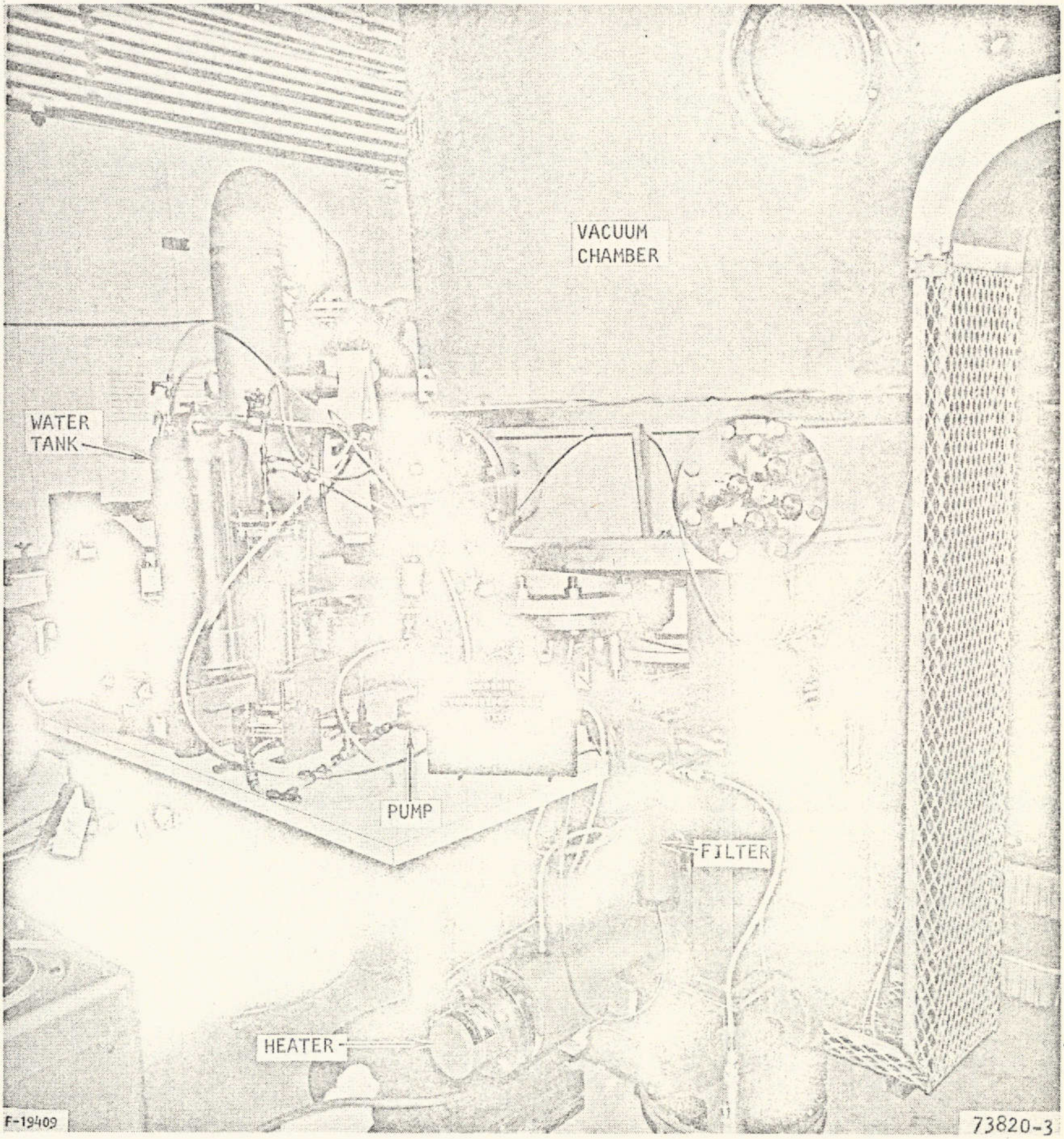

Figure 2-1. Test Setup

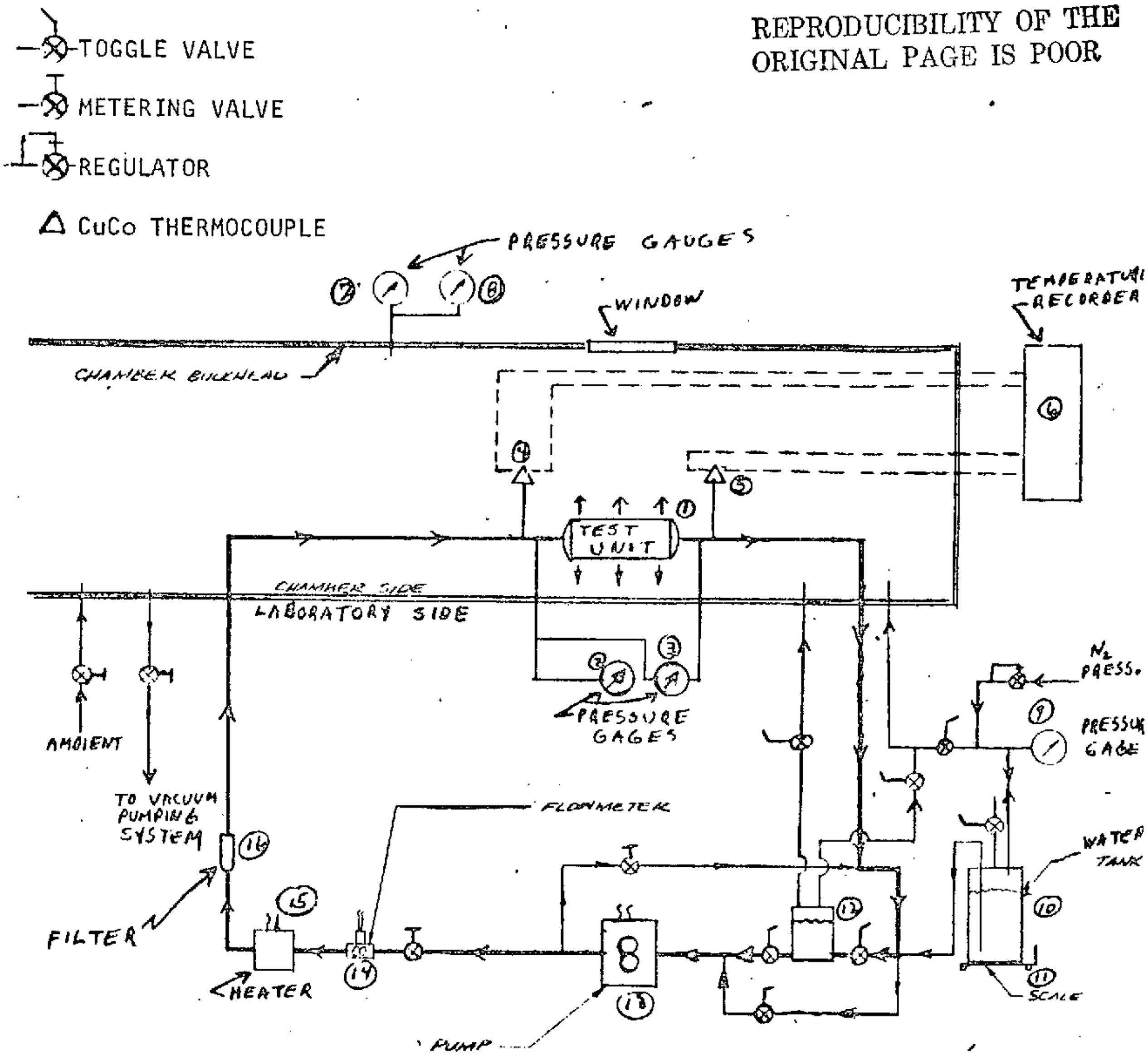

Figure 2-2. Test Setup Schematic

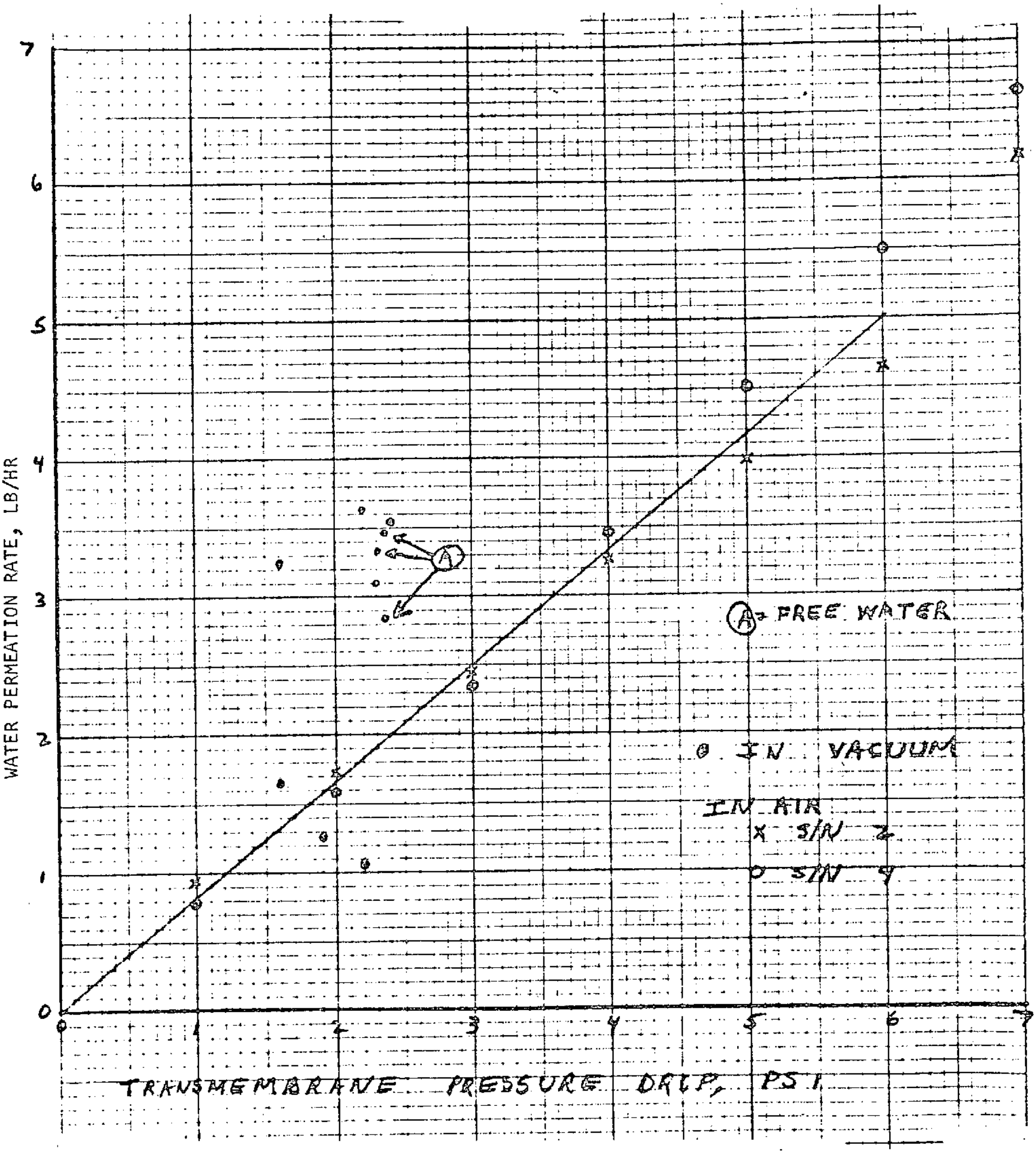

Figure 2-3. Cellulose Acetate Unit Permeation Rate

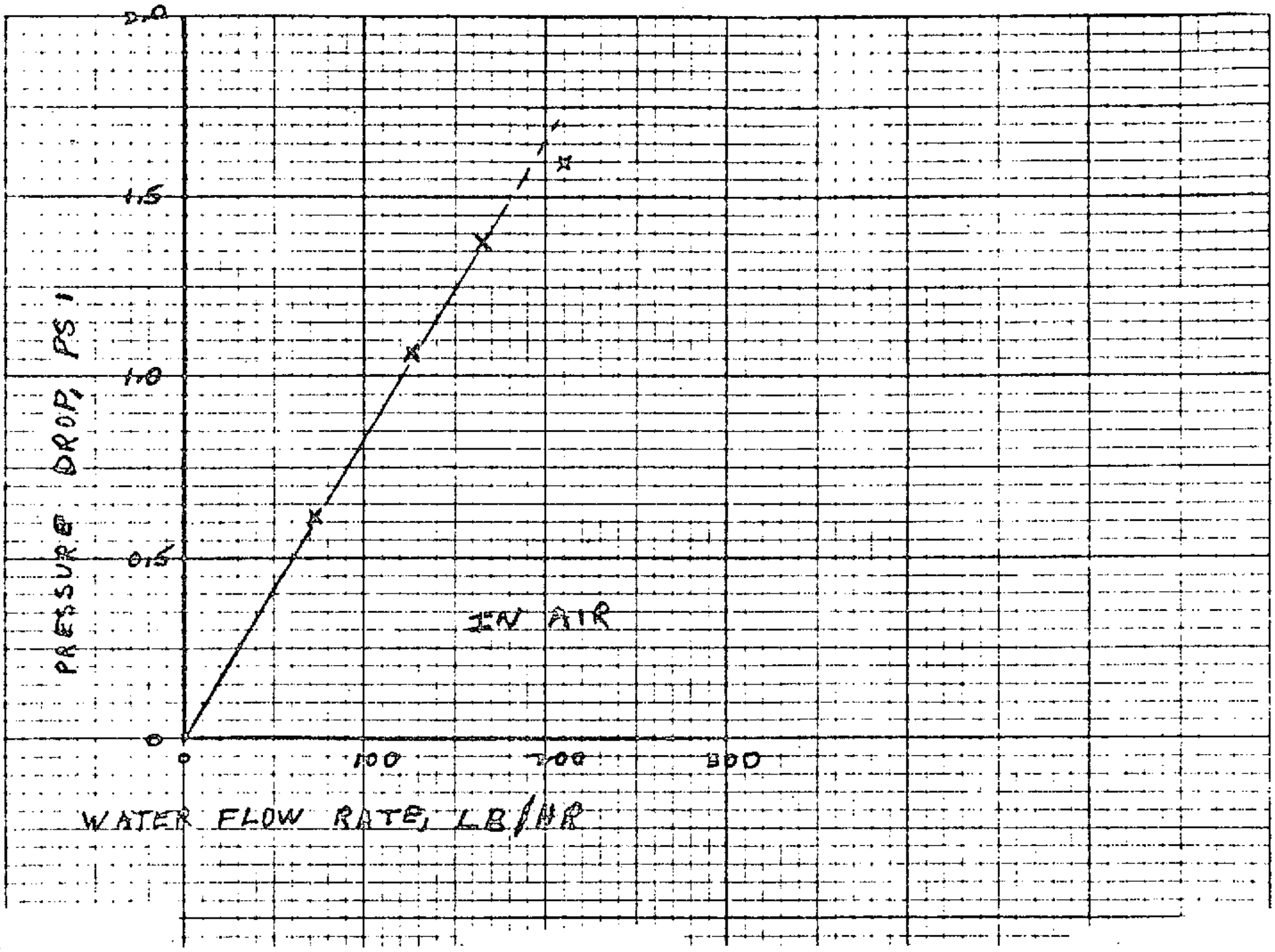

Figure 2-4. Tube Side Pressure Drop for
Cellulose Acetate Unit

TABLE 2-2

TEST SETUP COMPONENTS AND FUNCTIONAL DESCRIPTION

ITEM NO.	COMPONENT	DESCRIPTION
1.	Test Unit	Hollow fiber membrane unit made of (1) cellulose acetate and of (2) cellulose.
2.	Pressure Gage	Measures inlet pressure to unit. Range 0-20 psia, total accuracy ±0.5% of F.S. (full scale).
3.	ΔP Gage	Measures pressure drop across unit. Range 0-10 psi, total accuracy ±0.5% of F.S.
4.	Thermocouple	Connected to recorder, measures water inlet temperature to unit. Accuracy ±1°F on readout.
5.	Thermocouple	Connected to recorder, measures water outlet temperature from unit. Accuracy ±1°F on readout.
6.	Temperature Recorder	Connect to thermocouples. Accuracy ±1°F on readout.
7.	Pressure Gage	Measures chamber pressure. Range 0-35 psia, total accuracy ±0.25% of F.S.
8.	Pressure Gage	Measures chamber pressure duing vacuum testing. Range 0-20 mmHg, total accuracy ±0.25% of F.S.
9.	Pressure Gage	Measures water storage tank pressure. Range 0-100 psia, total accuracy ±0.3% of F.S.
10.	Water Storage Tank	Stores water used during evaporation/sublimation tests.
11.	Scale	Used to determine rate at which water is being used for evaporation/sublimation. Range 0 to 100 lbs, smallest increment of measurement 0.01 lb, accuracy 0.01 lb.
12.	Air Trap	Removes gas from recirculating water.
13.	Pump	Recirculates water through test system.
14.	Flowmeter	Measures the water recirculating rate. The flowmeter is a Cox turbine meter which is read out on an Hewlett Packard 5221A counter. Range 0-400 lb/hr, total accuracy ±1% of F.S.

TABLE 2-2

(Continued)

ITEM NO.	COMPONENT	DESCRIPTION
15.	Heater	Reheats the cold water returning from the test unit.
16.	Filter	Removes particulate matter from recirculating water loop. Rating 2 μ absolute.

TABLE 2-3

CELLULOSE ACETATE UNIT PERFORMANCE DATA

Chamber Pressure, mm Hg	Membrane Unit Conditions: Flow In, lb/hr	Unit Inlet Pressure psia	Unit ΔP, psia	Inlet Temp °F	Outlet Temp °F	Measured Water Loss, lb/hr	Calculated Water Evaporation Rate, lb/hr	Calculated Heat Rejection Btu/hr	Free Water Loss[4] lb/hr
Water Utilization Test									
6.7	50	2.6	0.79	67	44	1.09[1]	1.07	1090	0
6.9	50	1.8	0.40	80	44	1.65[2]	1.67	1820	0
6.7	100	2.2	1.10	80	45	3.26[3]	3.25	3540	0
Performance Tests									
7.5	50	2.1	0.38	71	44	—	1.26	1370	0
6.7	100	2.9	1.00	81	43	—	3.53	3340	0
6.8	100	2.7	1.00	85	46	—	3.62	3950	0
7.9	101	2.9	1.15	81	48	—	3.10	3380	0
4.9	168	7.8	5.4	108	34	—	11.4	12460	0
4.7	225	9.6	6.8	81	32	—	10.2	11030	0
Performance Tests with Free Water Loss									
6.8	100	2.6	0.6	79	44	—	3.25	3540	0.09
6.9	100	2.7	0.7	80	44	—	3.34	3640	0.12
9.8	100	3.0	1.3	80	51	—	2.70	2950	0.13

(1) Averaged over 2.5 hr period
(2) Averaged over 2.0 hr period
(3) Averaged over 3.0 hr period
(4) Visually observed droplets, assuming 20 droplets equals one ml.

After the last data point shown in Table 2-3 was obtained, all conditions were maintained constant and the chamber pressure was reduced to 2.5 mm Hg, well below the triple point of water (4.58 mm Hg). When this was done, the outlet temperature of the unit quickly dropped to 32°F and the unit started to freeze, as evidenced by an increasing pressure drop across the unit. The chamber pressure was then quickly increased and the unit unfroze but it was noted that some tubes were broken and the pressure drop across the unit was higher than originally. Because of the configuration of this particular unit and its characteristics, it was impossible to run the unit in the sublimitation regime without freezing.

Since the permeability of the water vapor in vacuum was found to be higher than that obtained in air (Figure 2-3) and, in fact, was more than adequate for the problem statement, it was decided to test the cellulose unit.

Initially, data was obtained on the cellulose unit for water permeability in air and for pressure drop. The permeability of the cellulose membrane to water as a function of the pressure differential across the membrane is shown in Figure 2-5. The data points in this figure are shown both for data obtained in air and for the calculated water rates through the membrane when in the vacuum chamber. For the air data, the measured permeation rate is shown, as the unit was received from the manufacturer, after the outer shell was removed from the unit and after some system tests were conducted. There is some difference in the permeation data for these conditions. The two most significant items shown in the figure are that the permeation rate for water is much greater when the unit is in vacuum and also the rate no longer appears to be a function of trans-membrane pressure differential.

Flow pressure drop data are shown in Figure 2-6 for the cellulose unit. The data here were obtained at four average inlet unit pressures. There appears to be some tendency toward lower pressure drops at higher inlet pressures. This might be due to the fact that the hollow fiber tubes are yielding slightly.

It was found, as expected, that the cellulose unit could operate at higher water inlet pressures without free water being formed on the shell side of the unit. Thus, it was possible to obtain higher flow rates through the unit and

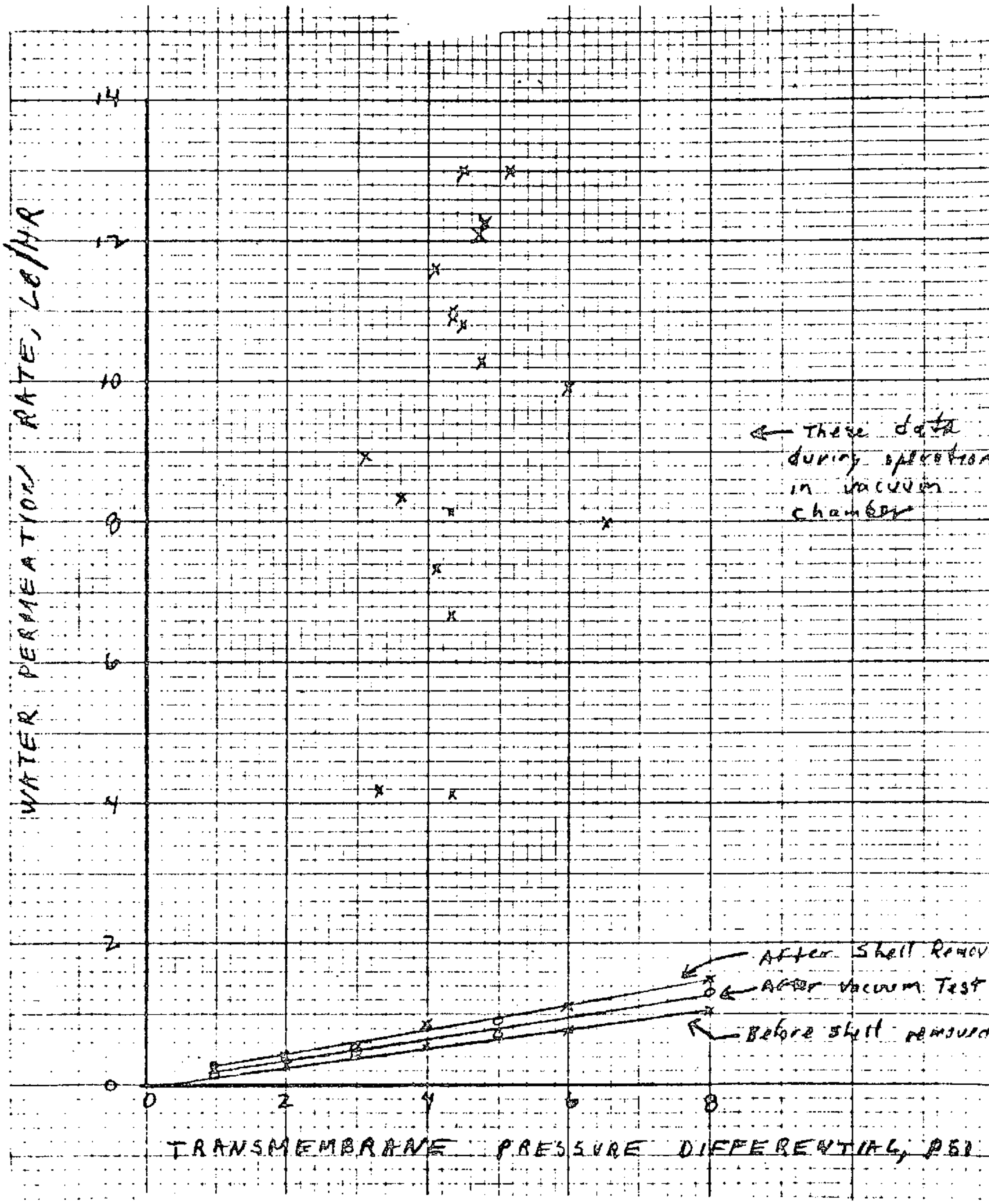

Figure 2-5. Cellulose Unit Water Permeation Rates

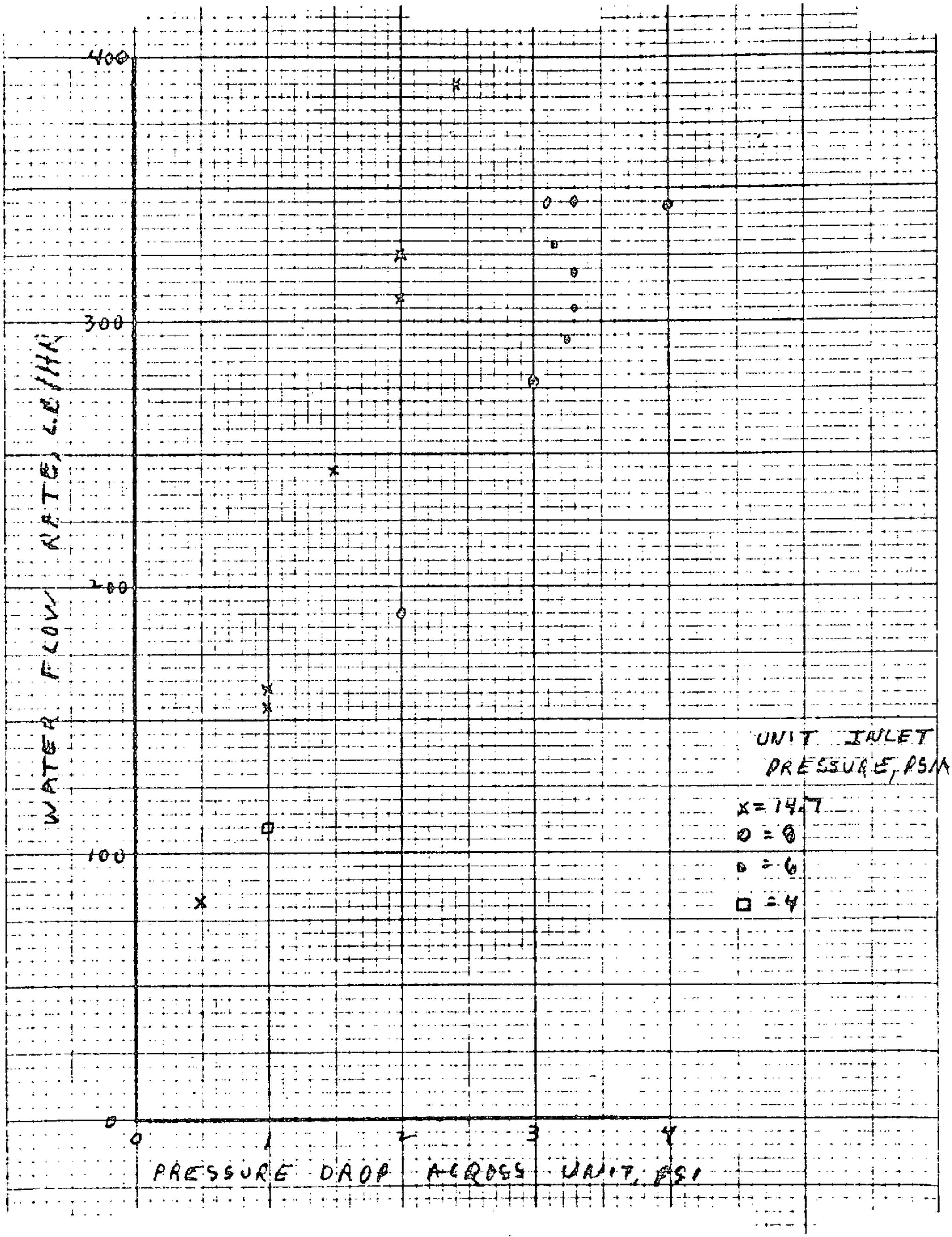

Figure 2-6. Cellulose Unit Pressure Drop

a larger range of flows. The results of the performance tests conducted with the cellulose unit are shown in Table 2-4. Tests were conducted on this unit both in the evaporation regime and in the sublimation regime. The unit operated satisfactorily in both regimes. Because of the higher flow rates that were obtained with the cellulose unit, the unit generally also had higher heat rejection rates; that is, the flows were such that high heat rejection rates could be obtained without the unit outlet temperature approaching the freezing point.

A series of tests were also conducted and data obtained for several cases where there were actually water dripping from the unit. These are also shown in Table 2-4. After these tests were conducted by NASA direction, further testing was halted.

TABLE 2-4

CELLULOSE UNIT PERFORMANCE DATA

Chamber Pressure psia	Membrane Unit Conditioning					Calculated Water Evaporation Rate, lb/hr	Calculated Heat Rejection Btu/hr	Free Water Loss, lb/hr
	Flow In lb/hr	Unit Inlet Pressure psia	Unit ΔP, psi	Inlet Temp, ^oF	Outlet Temp, ^oF			
Performance Tests as an Evaporator								
7.7	344	8.0	4.0	78	48	9.90	10,478	0
6.65	278	8.0	3.0	77	47	7.99	8,460	0
7.8	330	6.8	3.3	90	49	13.03	13,752	0
8.0	345	6.0	3.3	83	50	10.97	11,582	0
8.0	345	6.0	3.3	80	47	10.92	11,549	0
7.4	305	6.0	3.3	73	45	8.15	8,646	0
7.95	319	6.0	3.3	69	47	6.71	7,119	0
5.85	294	6.0	3.25	53	38	4.15	4,435	0
7.7	329	6.0	3.15	82	48	10.75	11,358	0
7.5	345	6.0	3.1	89	50	12.99	13,689	0
8.1	300	5.6	3.0	90	50	11.58	12,200	0
5.1	277	5.5	2.9	74	40	8.94	9,489	0
7.4	214	5.0	1.85	80	44	7.36	7,792	0
8.8	241	4.6	2.0	86	50	8.36	8,826	0
6.7	110	4.0	1.0	82	42	4.19	4,442	0
Performance Tests as a Sublimator								
1.8	316	6.6	3.7	81	47	10.30	10,900	0
2.2	322	6.5	3.6	85	46	12.10	12,790	0
2.4	305	6.5	3.5	86	44	12.28	12.910	0
Performance Tests with Free Water Loss								
7.2	360	8.0	4.3	53	43	3.36	3,637	0.099
8.0	355	8.0	4.0	56	47	2.99	3,240	0.185
7.8	170	8.0	2.0	82	44	6.00	6,532	0.218
7.5	192	6.0	2.0	54	44	1.79	1,942	0.112
7.1	90	6.0	1.0	82	43	3.26	3,546	0.278
7.7	310	5.9	3.1	51	46	1.45	1,579	0.146
7.5	90	5.8	1.0	89	44	3.75	4,095	0.192
7.2	130	4.0	1.0	53	44	1.09	1,183	0.073

SECTION 3

MEMBRANE PERFORMANCE ANALYSIS

INTRODUCTION

Permeation through polymeric materials is often assumed to occur by the mechanism of activated diffusion. This model assumes that permeation is basically a three step process. First, the permeating molecules dissolve in the polymer. Second, the molecules diffuse through the polymer. Finally, the molecules come out of solution on the downstream side of the polymeric membrane. The diffusion process is believed to depend on the formation of "holes" in the polymeric network, due to thermal agitation of the chain segments*. The diffusional driving force for this mechanism can be shown to be equal to the chemical potential gradient across the membrane**. For an infinitely dilute solution (of permeant in polymer), the chemical potential gradient is proportional to the concentration gradient.

The solubility of the permeating material in the polymer is assumed to follow Henry's law, i.e., the concentration is proportional to the partial pressure of the permeating molecules. Thus, the driving force for activated diffusion of a dilute solution is proportional to the partial pressure difference in the bulk fluid phases on either side of the polymeric membrane. The direction of permeation is, of course, from the high concentration side to the low concentration side.

The activated diffusion model does not fully describe the mass transfer mechanism for all cases. Other mechanisms, or combination of mechanisms, including continuum or rarefied fluid flow, may be the controlling mechanism. Some experimenters have found a total (rather than partial) pressure driving force for bulk phase liquid permeation***. In this program, for cellulose and cellulose acetate in air, it has been found that the permeation rate of water

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*A. Lebovitz, Modern Plastics, 43, 139 (1966).

**S.B. Tuwiner, Diffusion and Membrane Technology (Reinhold Publishing Corp., New York City, 1962), p. 38.

***L.B. Ticknor, J. Phys. Chem. 62, 1483 (1958).

is a function of total transmembrane pressure differential. When the membrane material is placed in a vacuum, the water permeation rate is no longer a function of transmembrane total pressure differential. This can be seen for cellulose acetate in Figure 2-3; for cellulose in Figure 2-5.

Several observations can be made from the cellulose acetate data shown in Figure 2-3. In vacuum, the water permeation rate appears to be independent of the transmembrane pressure differential. Free water apparently is also not a function of transmembrane pressure differential only. The data points noted by Ⓐ are for free water. Although the permeation rates with free water are well above that obtained in air, several other data points in vacuum had similar and higher rates without free water formation.

WATER UTILIZATION TEST

The purpose of the water utilization test was to determine the amount of water actually lost through the membrane with that which would be expected from the measured cooling rate. Net water loss rate was determined from the water inlet flow and inlet and outlet temperatures as follows. The heat and mass balances across the unit are:

$$\dot{m}_2 h_2 = \dot{m}_1 h_1 - \dot{m}_3 h_3$$

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

where $\dot{m}$ = water or steam mass flow rate, lb/hr

h = enthalpy, Btu/lb

1 = inlet water

2 = steam

3 = outlet water

Solving for the net water loss (or steam rate):

$$\dot{m}_2 = \frac{\dot{m}_1 \, (h_1 - h_3)}{(h_2 - h_3)}$$

and the heat rejection is simply m_2h_2. Flow and temperature data yield m_1, h_1 and h_3. Steam enthalpy (h_2) is found assuming saturation at an average between the inlet and outlet temperatures. The water loss rate and heat rejection values shown in Tables 2-3 and 2-4 were calculated from the above equations.

For the three water utilization tests the measured and calculated values agree within two percent (Table 2-3). This is within instrumentation accuracy of the test setup. It is believed that a more sensitive method of determining water utilization was by visual observation. An easily observable loss rate of a drop per five minutes represents a water utilization of over 99.95 percent; for those runs with no free water present, higher utilization than this value was probably obtained.

COOLING CAPACITY

One of the most significant operating characteristics of the membrane unit is shown in Figures 3-1 and 3-2. As noted earlier, the permeation rate in air is a function of transmembrane pressure differential (Figures 2-3 and 2-5). In a vacuum, the unit operates as if some form of activated diffusion was the controlling mechanism and the diffusional resistance was negligible. In other words, the driving mechanism for permeation may be the partial pressure of water vapor and thus the outlet liquid water vapor pressure of the unit is close to the vacuum chamber pressure.

For both the cellulose and cellulose acetate units, in the evaporation regime, the outlet water temperature was always within six degrees of the saturation temperature as shown in Figures 3-1 and 3-2. This occurred over a wide range of water flow rates (50 to 360 lb/hr), inlet temperatures (51 to $108^{\circ}F$), and inlet pressures (1.8 to 9.6 psia).

For the cellulose unit, the heat rejection capacity decreased when the pressure was reduced below the triple point and sublimation occurred. The reason for this is unclear, the fiber surfaces took on a sheen when the unit was operated as a sublimator. The sheen probably was due to some ice formation on the outer surface; the ice may have reduced or otherwise changed the permeation characteristics.

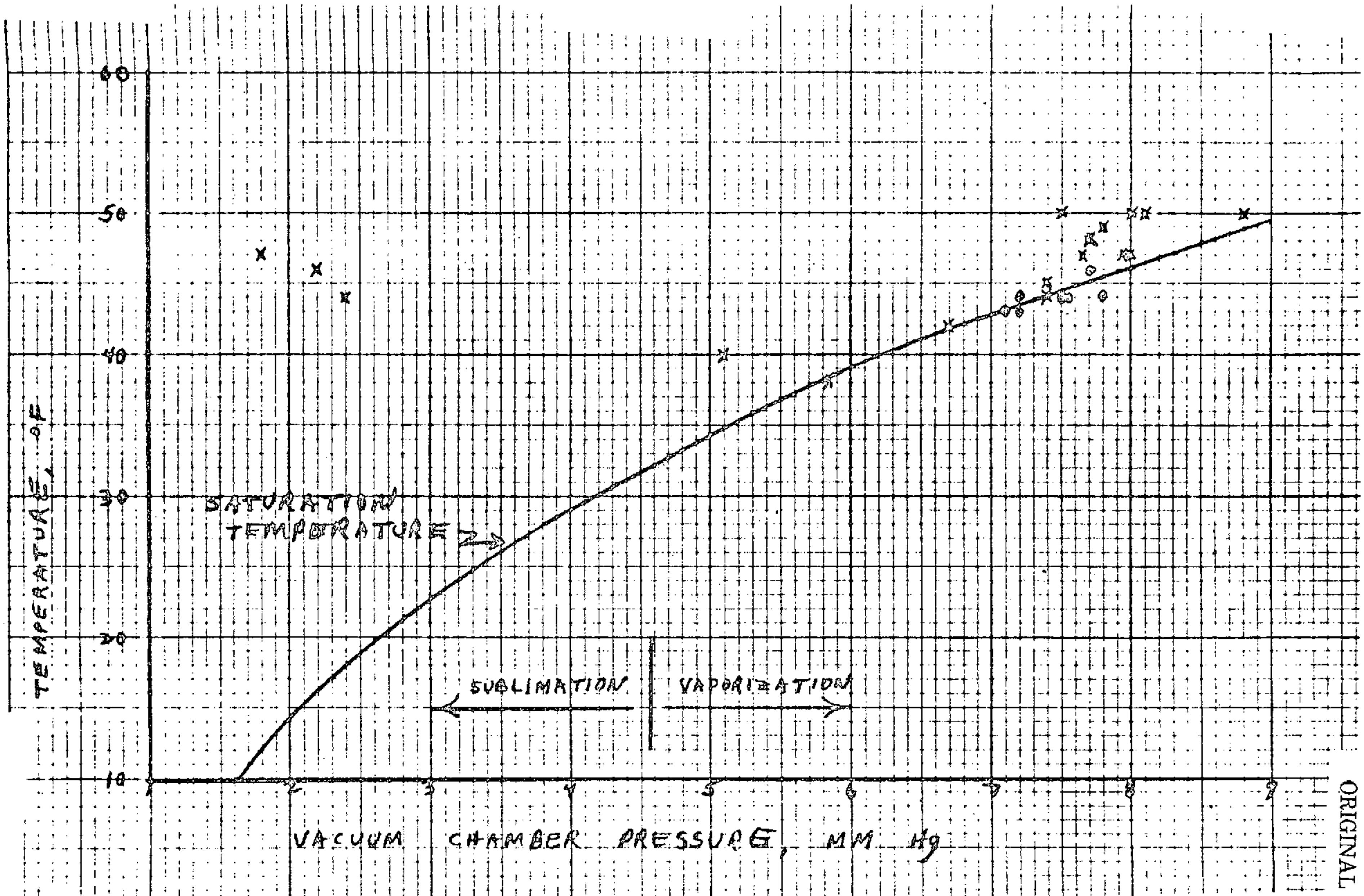

Figure 3-1. Water Outlet Temperature, Cellulose Unit

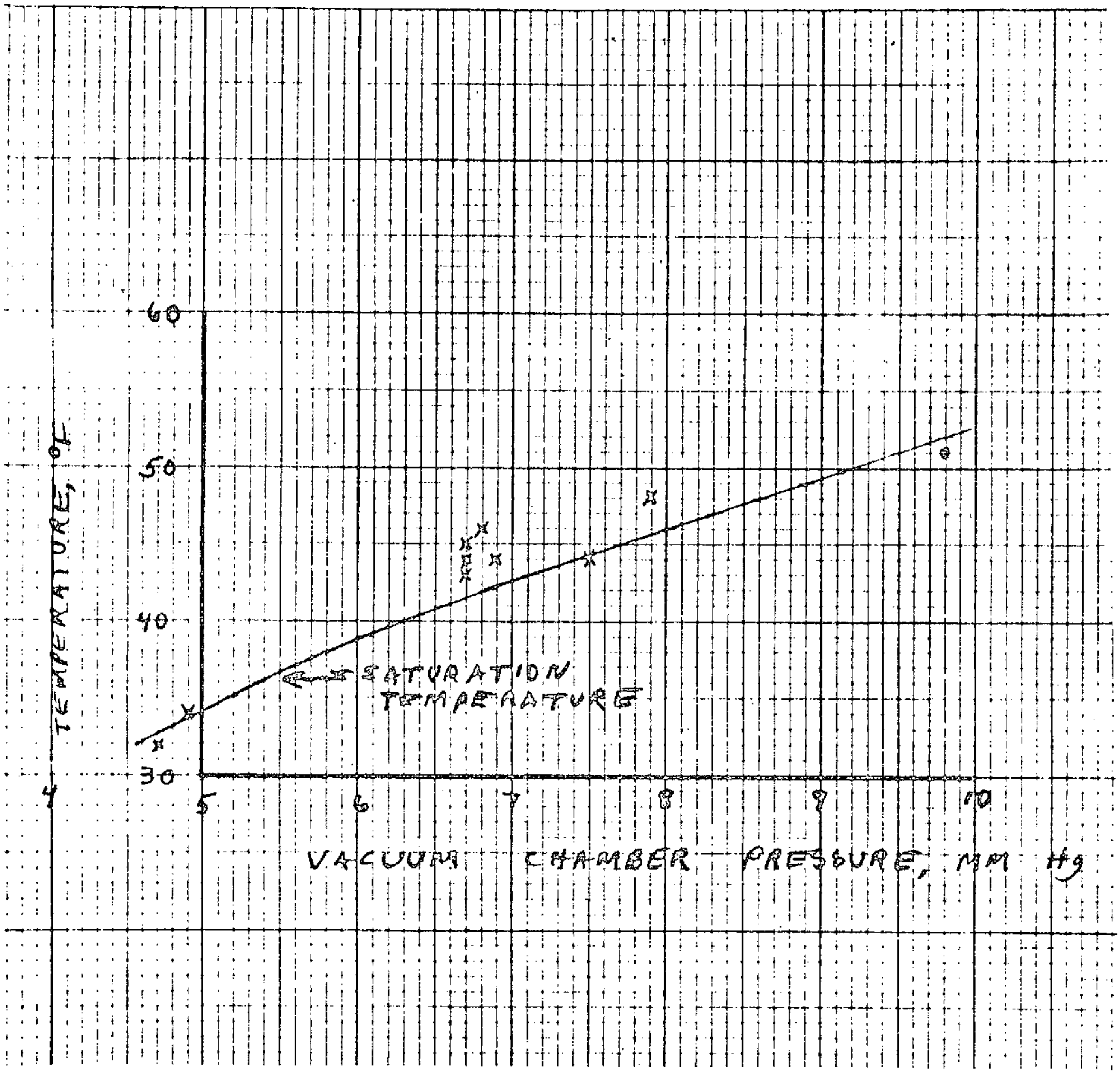

Figure 3-2. Water Outlet Temperature, Cellulose Acetate Unit

In Figures 3-1 and 3-2 the crosses are data obtained with no free water and the circles are data points where free water was observed. Generally, the free water data points are closer to the saturation curve than are the others. This relates to a baseline permeation and a cooling availability which is discussed below.

FREE WATER

When operated in a vacuum, there apparently is a minimum permeation rate for these units which may be a function of several variables such as transmembrane pressure differential, vacuum chamber pressure and temperature. Figure 3-3 shows a general correlation between available cooling capacity and transmembrane pressure difference. Available cooling capacity is here defined as the quantity of cooling obtained at the given flow rate between the water inlet temperature and an outlet temperature equal to the saturation temperature at the vacuum chamber pressure. Below the dotted line, there is a tendency for free water to be formed; operation above the line is desirable.

For the units tested, the tube bundle was tightly packed with a relatively large diameter. There was some concern that the steam side pressure drop might be high enough to either limit the permeation rate (and cooling capacity) or cause free water to form.

A computer program was developed to calculate the steam pressure drop on the shell (vacuum) side of a membrane tube evaporator. The model assumes that the membrane tubes are uniformily spaced with the same average spacing as found in the actual tube bundle. For cylindrical bundles the tubes are arranged in concentric rings of constant radial dimension, while in rectangular bundles the tubes are arranged in parallel rows. The number of rings (or rows) is rounded to the nearest integer value, but the number of tubes in each ring (row) is allowed to have a fractional remainder. The volume and configuration of the model tube bundle closely approximate those of an actual bundle.

The total steam flow rate is an input value. For the model it is assumed that this flow rate permeates uniformily from all tube surfaces, so that the flow rate at each tube ring (or row) is easily calculated. The minimum flow

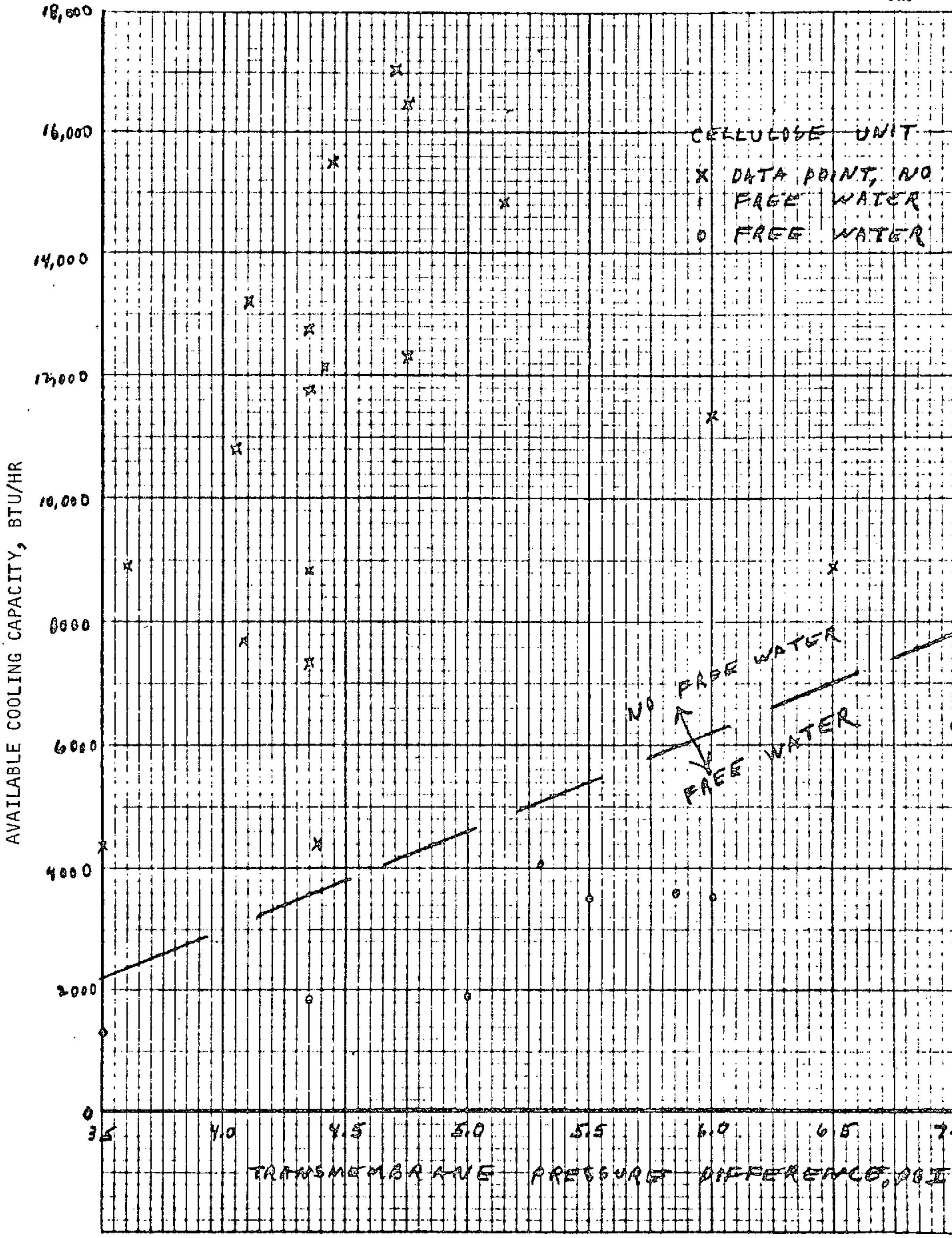

Figure 3-3. Free Water Formation Regime

area between tubes at each ring is computed from the model's geometric properties. Pressure drop at each ring is then calculated using an equation* for laminar flow across the tube banks:

$$\Delta P = 4f\ NG_{max}^2/2g_c\rho$$

and

$$f = \frac{26.5\ (L_p/D_v)}{\left(\frac{D_v\ G_{max}}{\mu}\right)}$$

where

P	=	pressure
f	=	friction factor
N	=	no. of tubes rows (N-l in model)
G_{max}	=	W/A_{min}
W	=	steam flow rate
A_{min}	=	minimum area between tubes
g_c	=	conversion factor
ρ	=	steam density
D_v, L_p	=	geometric properties
μ	=	steam viscosity

The program starts with the known pressure outside the bundle and calculates the pressure drop across the outermost tube ring using the above equation. This pressure drop is added to the known pressure to obtain the pressure between the outer ring and the next ring in. This procedure is repeated for each ring working inward to the center.

*McAdams, "Heat Transmission", Chapter 6, Ed. 3, 1954, McGraw-Hill

The saturation temperature profile for the membrane test units are shown in Figure 3-4 for two different chamber pressures. Comparing the centerline saturation temperatures with the steam rate data in Tables 2-3 and 2-4, it is apparent that for the high cooling conditions, the center core of the tube was being restrictive. Unit outlet temperatures for almost all cases at the given permeation rate are well below the calculated centerline saturation temperature. It is probable that the permeation rate through each tube was not the same, as assumed in the model, rather the permeation rate increased from the center of the bundle to the outside ring of tubes. It also is probable that the rate also simultaneously varied in the axial direction, being greater at the inlet (high temperature) end of the tube bundle, where the vapor pressure and thus the driving force was greater.

FLIGHT UNIT

The evaporator/sublimator problem statement, for the task order, is shown in Table 3-1, and is for the LCG (liquid cooled garment) recirculating loop. One can consider two concepts to achieve the desired heat rejection, (1) constant cooler outlet temperature with variable flow to the crewmen or (2) variable outlet temperature with constant flow to the crewman; as shown in Figures 3-5 and 3-6. From a comfort viewpoint the constant flow concept is preferable. The other concept (Figure 3-6) was used on ALSA, this eliminated the need for an additional water line in the umbilical.

TABLE 3-1

EVAPORATOR/SUBLIMATOR PROBLEM STATEMENT

Water Flow, Rate, lb/hr	240
Pressure, psig	50
Allowable pressure drop, max psi	1
Heat Rejection	
Maximum	
Btu/hr	3088
Inlet temperature, min, $^{\circ}$F	54
Minimum	
Btu/hr	135
Inlet temperature, max, $^{\circ}$F	80

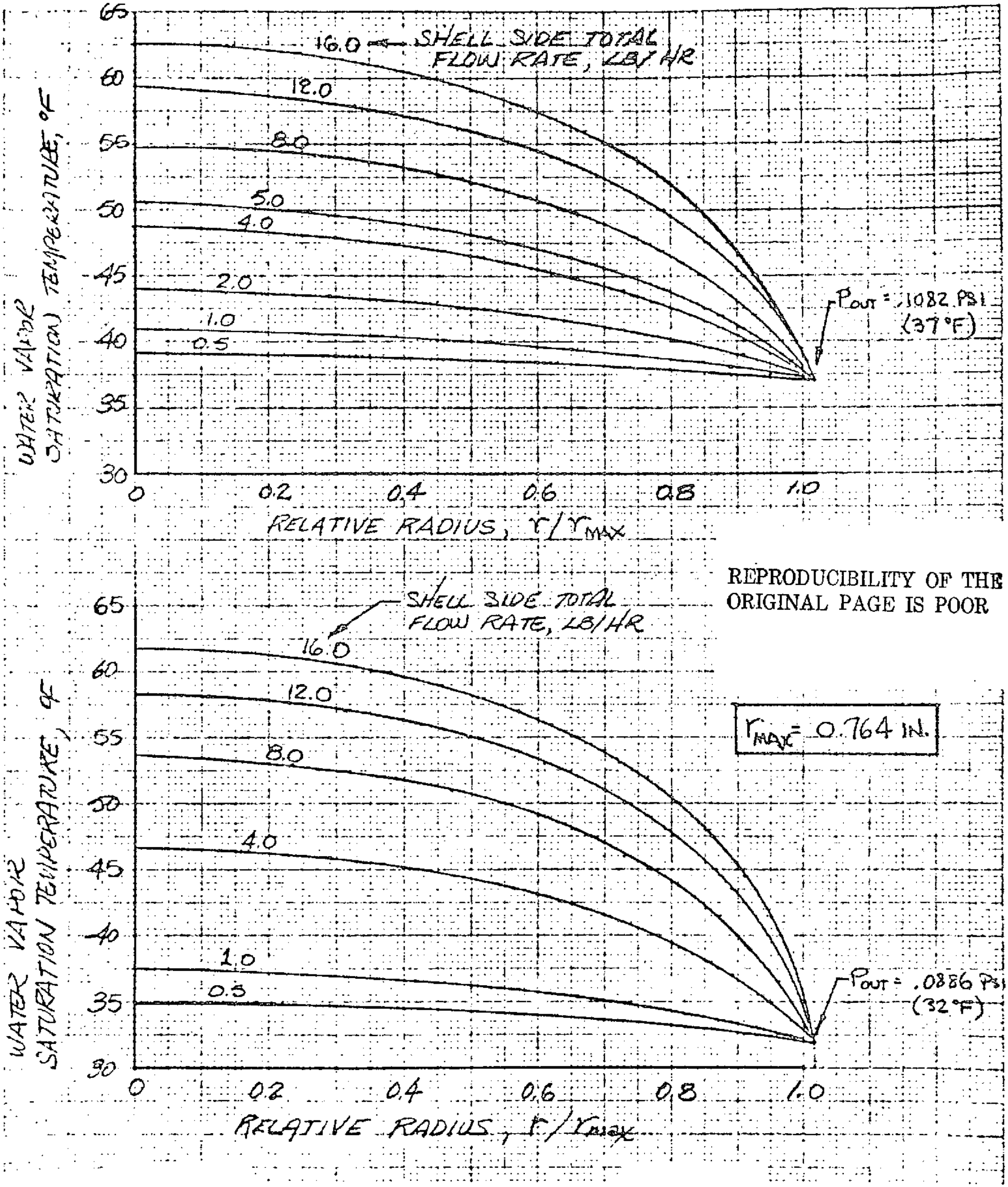

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Figure 3-4. Steam Rates and Saturation Temperature

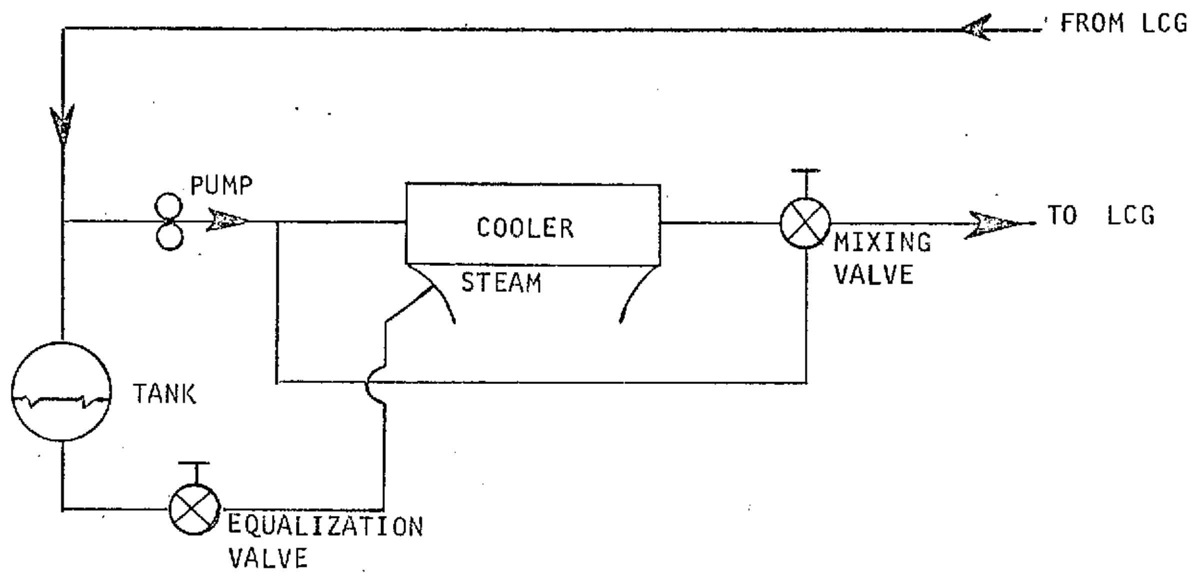


Figure 3-5. Constant Flow to Crew Adjustable Temperature

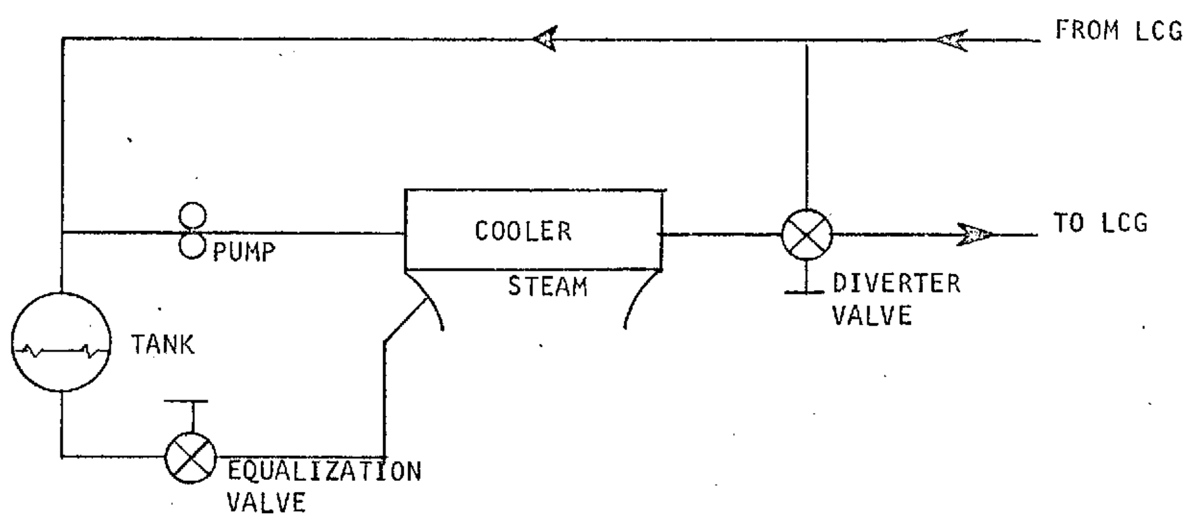


Figure 3-6. Constant Temperature to Crew Adjustable Flow

There are also two concepts for the cooler, evaporation or sublimation which can be used with either of the above LCG concepts. Evaporative cooling requires that the pressure above the evaporating water be kept above 4.6 mm Hg, this usually requires a valve on the outlet steam duct. If the sublimation concept is utilized, the unit is simply vented to space vacuum. Other requirements, such as a nonventing mode, may result in a steam shutoff valve.

Based on the test data reported above, a preliminary design configuration of a membrane unit was made for each concept. The membrane material for the sublimator was cellulose, for the evaporator, either cellulose or cellulose acetate are candidates. The quantity of membrane material used was one-fifth of that in the test unit. This will provide the 3088 Btu/hr maximum capacity and reduce the possibility of free-water at the minimum heat load. For both concepts, the membrane forms but a small part of the overall unit.

Sublimator

As shown in Table 2-4, a membrane unit adjusts automatically to a wide range of heat loads in the evaporation regime with the outlet temperature being a function of shell (vacuum chamber) side pressure (Figure 3-1). Unfortunately, the test program was halted before this automatic adjustment could be tested in the sublimation regime. However, since the outlet water temperature, at the same conditions, increased (Figure 3-1) when the vacuum pressure was reduced to the sublimation regime, there is a good possibility that the automatic control range, between freezing and free water droplets, may be greater in the sublimation regime than in the evaporization regime. If this proves correct, a rather small, simple flight unit would result. A preliminary design of such a unit is shown in Figure 3-7. Further reduction in size may be possible by using a concentric design with the steam duct in the center and the water passing through the concentric area. This was used for the evaporator unit, discussed below, the selection of either design would probably be dictated by packaging considerations. Weight of the unit shown in Figure 3-7 is 0.6 lb. For use in a nonventing mode and for checkout in the cabin; a steam side shut off valve should be added. Also, an equalization valve should be located between the LCG loop and the steam plenum chamber to equalize pressures on both sides of the membranes during those operations.

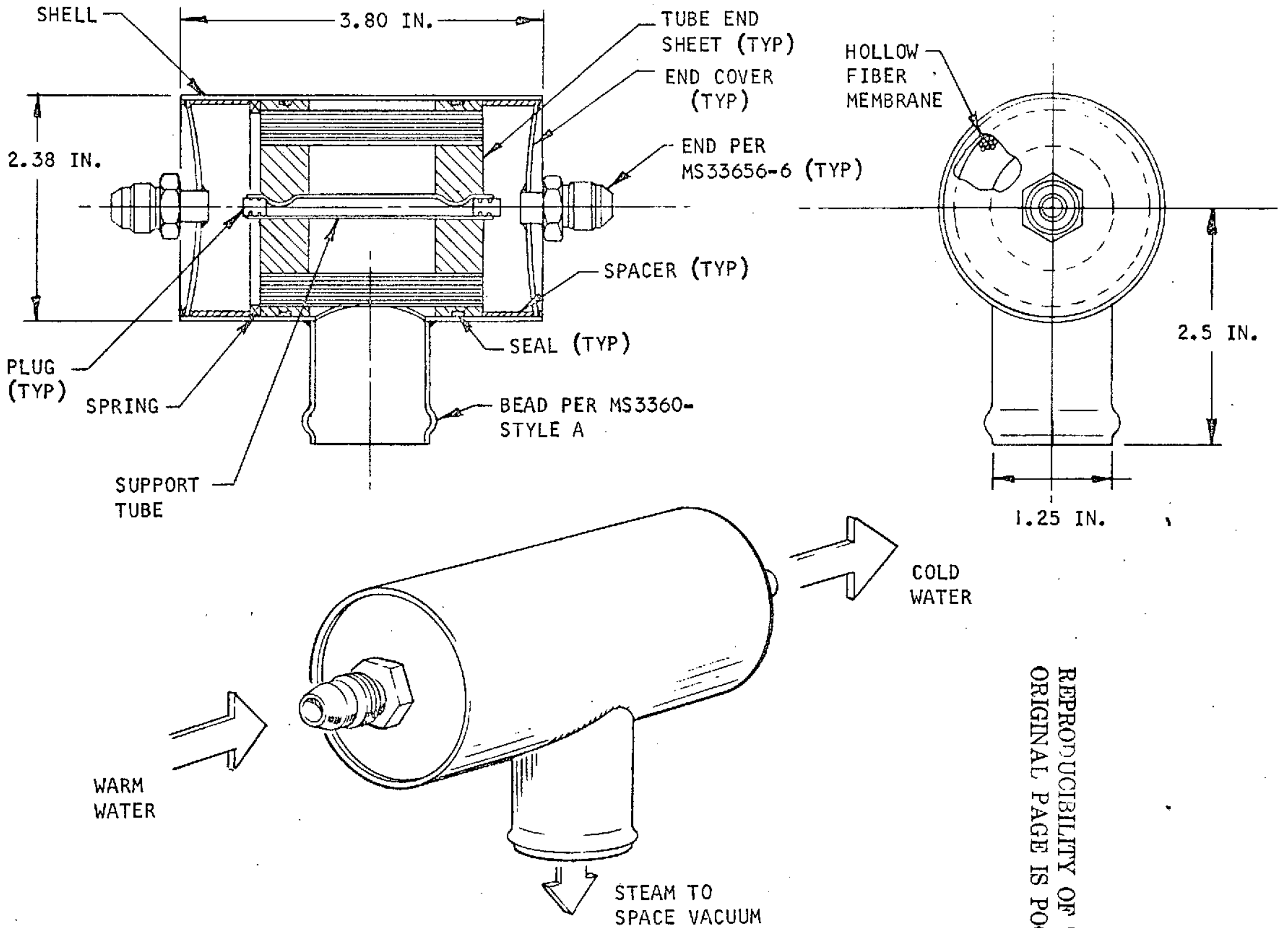


Figure 3-7. Membrane Sublimator

Evaporator

Since the actual membrane material forms a small part of the final unit, it was necessary to first develop a control concept. A review of thermal control/steam valves showed that the valve developed for the Gemini chestpack (ELSS) most closely fitted the present requirements. This valve was used in the evaporator-condenser and sensed and controlled the recirculating gas temperature to the 40 ±5°F. The unit featured a wax sensing element (Vernatherm) which drove a simple poppet valve (Figure 3-8). In addition, for checkout in the cabin, the unit featured a manually operated override which closed off the valve.

A check of the automated trouble report summary system for the Gemini ELSS revealed not a single instance of malfunction of this steam control valve during system level testing at AiResearch, manned chamber testing by NASA, or during mission flight activities.

A preliminary design of the evaporator cooler is shown in Figure 3-9. The unit consists essentially of two cylinders; water flows into the unit near the poppet valve down between the concentric cylinders then through the semi-permeable hollow fiber membranes, into the back center region of the unit where the water passes over two Vernatherm elements. The basic control mechanism is similar to the steam control valve on the Gemini ELSS; two Vernatherms are used here to get the required poppet travel and steam flow for the same size valve. Steam travels from the outside of the membrane fibers into the center of the unit and through the poppet. The unit has a built in shutoff valve for use when a nonventing mode is desirable. An equalization valve should also be added to the system as discussed previously.

Before selection of the best concept can be made further development testing will be required as discussed in Section 1.

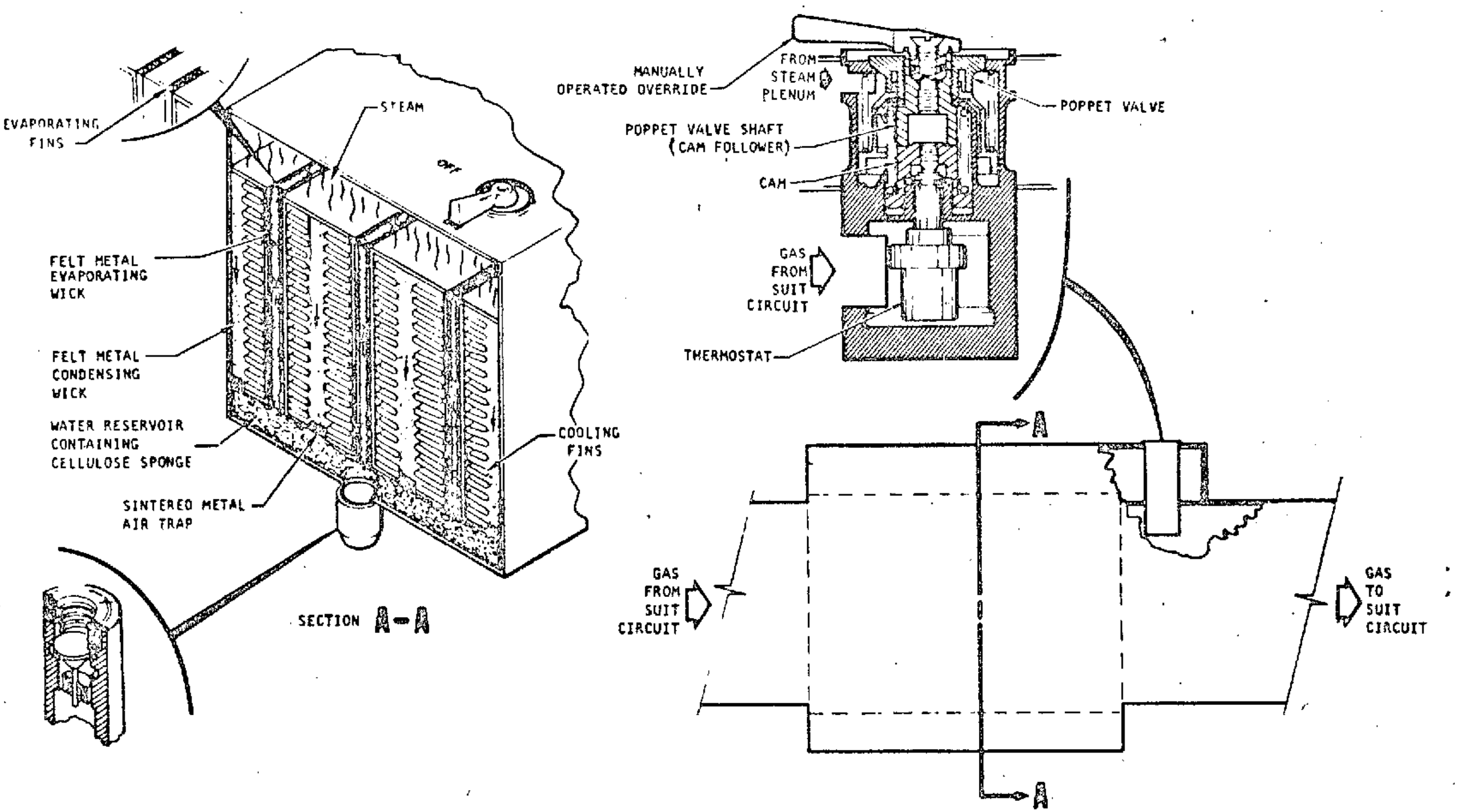
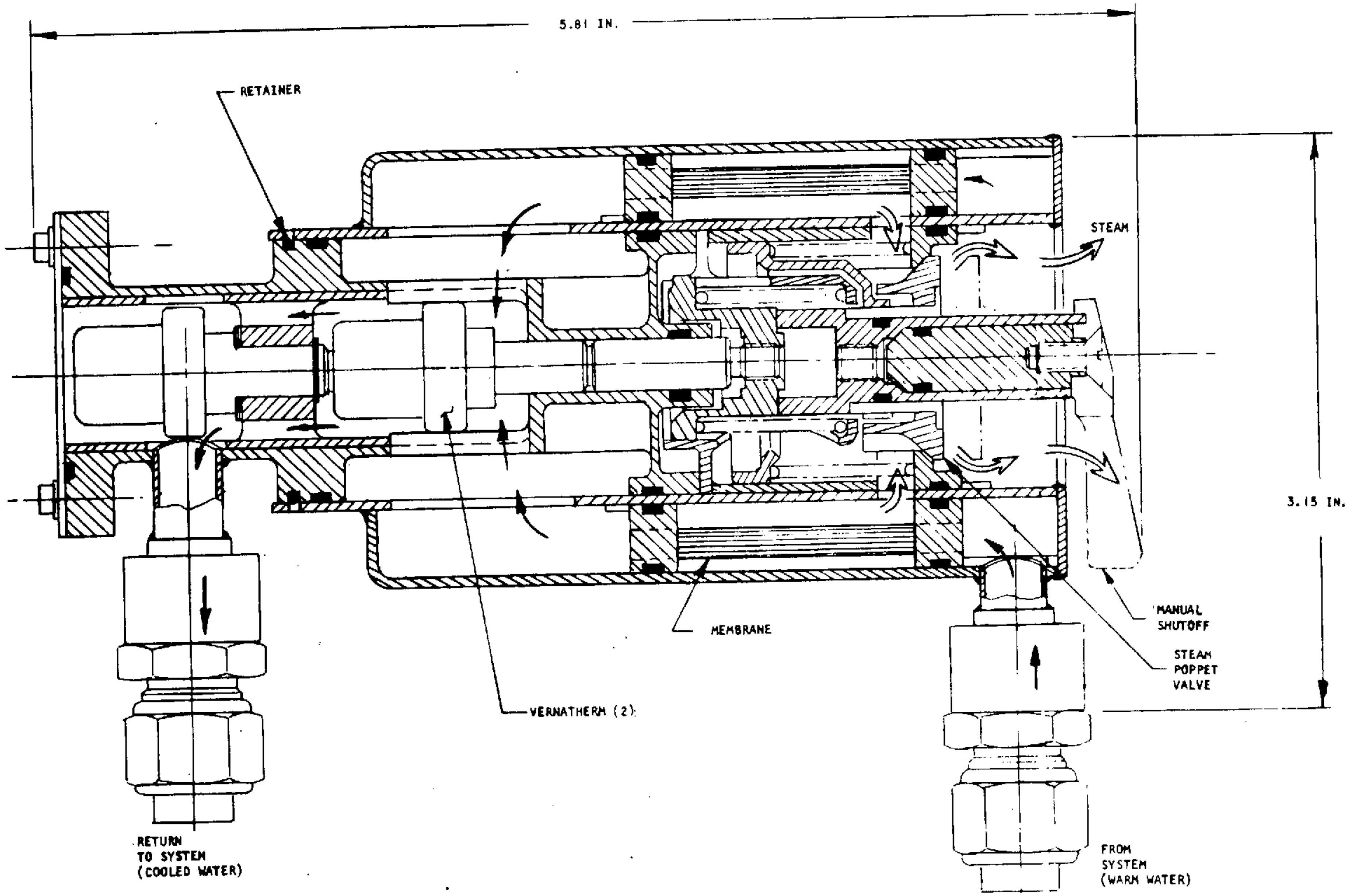


Figure 3-8. Gemini ELSS Evaporator Condenser



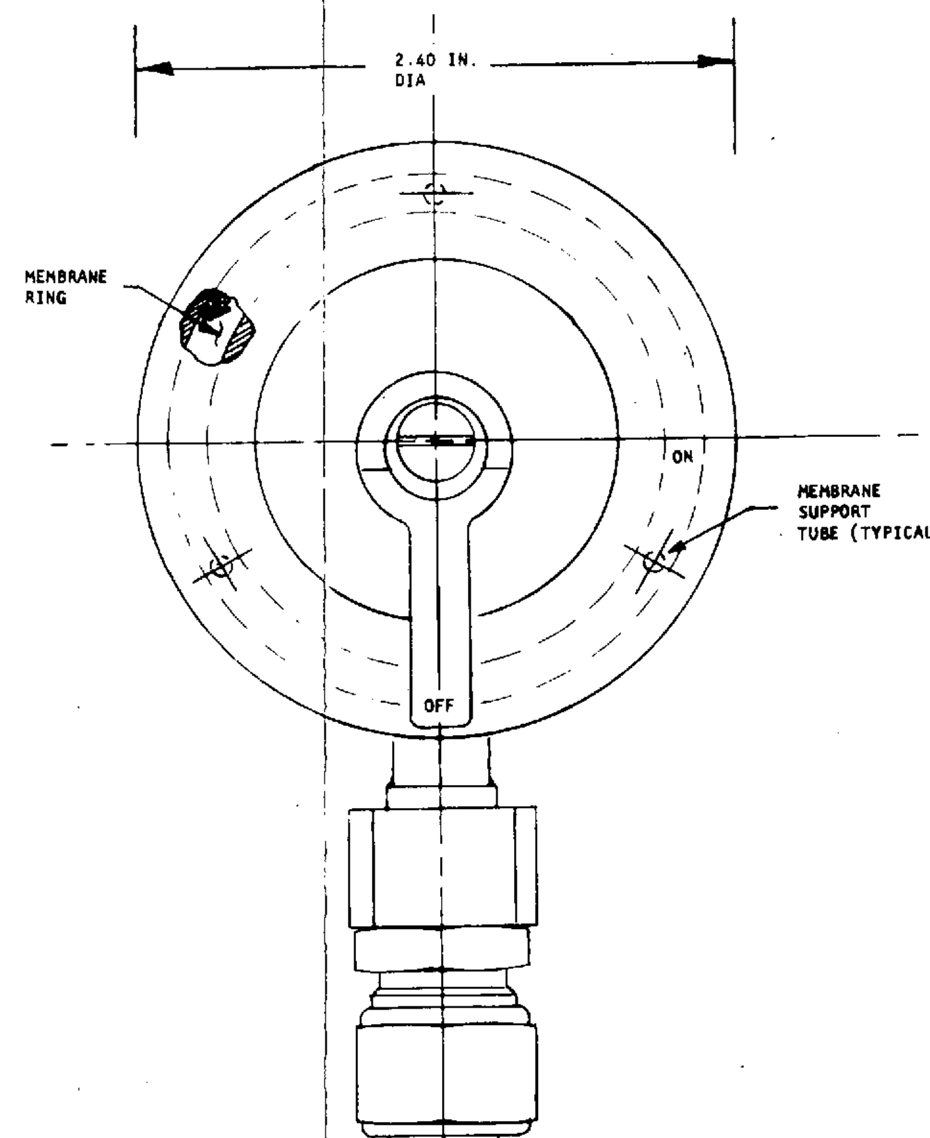


Figure 3-9. Membrane Evaporator